FINAL REPORT

RESEARCH ON

ACTIVE SUPPRESSION OF AERODYNAMIC INSTABILITIES IN CENTRIFUGAL COMPRESSORS

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INTRODUCTION

The operating range of a compressor is bounded by the surge and choke lines on a performance map. The barrier posed by the surge line is of particular interest due to its proximity to the maximum efficiency points of the compressor. Namely, the surge line separates the regions of stable and unstable compressor operation. As a result, adequate surge margin from the operating line must be provided, resulting in the machine not operating at maximum efficiency.

The term "surge line" on the performance map is somewhat misleading because surge is only one of the possible unsteady flow phenomena that occur when the surge line is reached. In general, two flow instability modes exist - rotating stall and surge.

Rotating stall is an instability local to the compressor. It is characterized by a circumferential nonuniform flow deficit, with one or more stall cells propagating around the compressor circumference at a fraction of impeller speed, typically from 10% to 30%. In fully developed rotating stall, the overall flow through the compressor is constant in time, with the stall cells redistributing the flow around the annulus. The formation of these rotating stall cells is surmised to result from an axisymmetric flow instability, with small circumferential nonuniformities growing into finite amplitude disturbances. In centrifugal machines, rotating stall is often subdivided into impeller stall and diffuser stall to differentiate where the effect of the distorted flow is strongest.

In contrast to rotating stall, surge is a global instability which involves an oscillation of the overall flow. Mild surge refers to a low amplitude, global oscillation of the mass flow through the compression system without any flow reversal occurring. Mild surge often precedes deep surge, which takes the form of a more violent oscillation, with the mass flow through the system reversing over a portion of the surge cycle. Surge is a phenomena of the entire compression system, consisting of the compressor and the system into which it discharges. The frequencies of surge are set by the system geometry rather than by that of the individual components. The frequencies are therefore independent of impeller speed and tend to be much lower than those of rotating stall.

PROBLEM STATEMENT

To develop high efficiency centrifugal compressors, the surge line must be extended to higher pressure ratios, thereby increasing the operating range and improving compressor efficiency. This requires a quantitative understanding of the fundamental unsteady flow phenomena which generate the surge line instabilities. Surge line control strategies and techniques can then be developed and successfully applied to a wide variety of centrifugal compressor configurations. In particular, active surge line control mathematical models which simulate the fundamental unsteady aerodynamic phenomena inherent in centrifugal compressors are needed. Also required are centrifugal compressor experimental data for model verification and to direct the development of advanced models as well as investigate and develop active control strategies.

RESEARCH OBJECTIVES

The overall objective of this research program was to improve centrifugal compressor performance by extending the surge line to higher pressure ratios. In particular, the objective was to develop active surge line aerodynamic instability control technology for centrifugal compressors with vaned diffusers so that the surge line will be moved to higher pressure ratios and the compressor can be matched at its peak efficiency.

Specific research objectives included the following.

* Determine the effect of centrifugal compressor design variables on the general effectiveness of active aerodynamic surge line instability control systems.
* Determine the effect of mean flow compressibility on active aerodynamic surge line control of centrifugal compressors with vaned diffusers.
* Experimentally investigate active aerodynamic surge line aerodynamic instability control in centrifugal compressors through the introduction of upstream vorticity.

Thus, the focal point of this research was directed towards an understanding of the fundamental driving fluid mechanics for surge line instabilities in centrifugal compressors rather than the development of complicated and expensive control systems.

TECHNICAL APPROACH

The technical approach necessary to achieve the objectives of this research program included both analysis and experiments.

To determine the effect of the various centrifugal compressor design variables on the general effectiveness of the active aerodynamic surge line instability control system, including the effect of mean flow compressibility, a mathematical model was developed. This model analyzed the effects of introducing a control inlet distortion, i.e., a control vorticity wave, on the potential instability waves which precede flow instability in the compressor, thereby delaying stability onset. The model is based on the assumption that the behavior of the compressor under a small distortion can be modeled by a linearized correction to the steady, axisymmetric pressure rise versus flow rate characteristic.

This model was utilized to determine the effect of the various centrifugal compressor design variables on the general effectiveness of active aerodynamic surge line instability control systems, including the effect of mean flow Mach number. This was accomplished by applying this model to a series of centrifugal compressor geometries, with the following parameters considered: radius ratio, area ratio, exit to mean inlet radius ratio, radial diffuser vane exit flow angle, and mean flow Mach number.

The experimental investigations were directed at investigating active aerodynamic control of surge line instabilities in centrifugal compressors with vaned diffusers. These experiments were accomplished in the Purdue Low Speed Centrifugal Research Compressor. This research compressor is a low speed, mixed flow compressor with a rotational speed of 1,800 RPM and a stagnation pressure ratio of 1.03:1. Air is drawn in through either an axial inlet or a vaned radial inlet section capable of introducing prewhirl. The shrouded impeller has an axial inlet, with the air exiting the impeller at an angle of approximately 85 degrees from the axial direction. The diffuser section also has turning vanes to reduce the tangential component of the air velocity.

The Purdue Low Speed Research Centrifugal Compressor with its variable geometry vanes made it ideal for this investigation, with impeller stall, diffuser stall, and surge having been demonstrated for various vaned diffuser configurations. Thus, control of phenomena analogous to those observed in high speed compressors could be quantitatively investigated with relaxed requirements for control actuator authority and response time. This allowed the focal point of this research to be directed toward an understanding of the fundamental driving fluid mechanics and active aerodynamic control technique rather than the development of complicated and expensive control systems.

RESULTS

Stall Initiation Experimental Investigation

The existence of weak precursor waves to rotating stall is a key assumption in both the mathematical model and the active control experiments. With regard to the experimental portion of this research program, the Purdue Low Speed Centrifugal Compressor has been instrumented to detect these precursor waves.

Eight circumferentially distributed microphones were installed in the inlet O.D. endwall, with an additional fifteen microphones placed in the diffuser O.D. endwall. The microphones are conventional audio types with the addition of a pneumatic attenuator designed to act as a physical low-pass filter. This modification allowed the high sensitivity of the devices to be preserved in the low frequency band of interest without saturating the microphones with signals generated from blade-pass and flow noise.

Signals from the microphones were sampled simultaneously as the compressor throttle was slowly closed. The resulting signals were numerically filtered to a 20 Hz band around the expected stall frequency. A spatial-domain Fourier transform was then performed on the data, resulting in time-history traces of the magnitude and phase of the circumferential harmonics in the flow field during stall initiation.

The goal of the experiments was to identify spatially coherent pressure waves which serve as precursors to the development of an instability in the Purdue Low Speed Centrifugal Research Compressor when configured with both a vaneless diffuser and also a vaned radial diffuser. With a vaneless diffuser, the transition to stall was observed to be a gradual process, with the growth of the pressure waves into those corresponding to a large scale stall condition occurring over a time span of 26 impeller revolutions. The behavior was typified by one or more weak circumferentially distorted pressure waves adjusting to the ultimate phase propagation velocity of the finite stall pattern shortly after arising from the background noise of unexcited spatial modes. The waves would then grow into a finite stall condition or dissipate as another stronger mode gained dominance over the flow field.

With the radial vaned diffuser, an unexpectedly broad variety of stall patterns was discovered as the compressor entered rotating stall and surge. Three different diffuser geometries were investigated, resulting in three different instability pathologies. In all cases, the transition to stall was gradual, with the growth of the pressure waves into those corresponding to a large scale stall condition occurring over a time span of between 15 to 25 impeller revolutions. In all cases of rotating stall, the behavior was typified by one or more weak, circumferentially distorted pressure waves adjusting to the ultimate phase propagation velocity of the finite stall pattern shortly after arising from the background noise of unexcited spatial modes. The waves would then grow into a finite stall condition or dissipate as another stronger mode gained dominance over the flow field. In all cases, the excitation of the pressure waves, as indicated by spatial Fourier analysis, occurred 5 to 15 impeller revolutions before small changes were evident in the raw microphone signals and 15 to 25 revolutions before the stall condition could be considered fully developed.

In the single case where a surge behavior was encountered, a rotating stall condition appeared to develop prior to the surge condition arising. In this case, as in the cases where rotating stall was the dominate instability, early warning of an impending stall condition was provided by the spatial Fourier analysis of the signals from the circumferentially distributed microphone arrays.

Thus, it is concluded that such techniques are viable in the detection of stall precursors in centrifugal compressors, with sufficient time for a control system to interact with the stalling process before highly nonlinear behavior is encountered.

Mathematical Model

Both an incompressible flow and a subsonic compressible flow math model were developed to predict the suppression of instabilities in a centrifugal compressor with a vaned diffuser. This model is based on a control waveform generated upstream of the impeller inlet to damp weak potential disturbances that are the early stages of rotating stall. The control system was analyzed by matching the perturbation pressure in the compressor inlet and exit flow fields with a model for the unsteady behavior of the compressor.

The model was shown to be effective at predicting the stalling behavior of the Purdue Low Speed Centrifugal Compressor for two distinctly different stall patterns. Predictions made for the effect of a controlled inlet vorticity wave on the stability of the compressor showed that for minimum control wave magnitudes, on the order of the total pressure disturbance magnitude, significant damping of the instability can be achieved. For control waves of sufficient amplitude, the control phase angle appeared to be the most important factor in maintaining a stable condition in the compressor.

The effect of introducing a lag to allow for the control wave to be convected through the compressor flow path in all cases was beneficial to the control effectiveness. The convected wave assumption also produced a shift in the phase angle for optimum control effectiveness.

PUBLICATIONS

The detailed results obtained in this research program are presented in the following technical papers.

Lawless, and Fleeter, S., "Active Control of Centrifugal Compressor Rotating Stall," *IUTAM 6th International Symposium on Unsteady Aerodynamics and Aeroelasticity of Turbomachines and Propellers*, The University of Notre Dame, September 1991.

Lawless, P. and Fleeter, S., "Active Unsteady Aerodynamic Suppression of Rotating Stall in an Incompressible Flow Centrifugal Compressor with a Vaned Diffuser," *International Journal of Turbo & Jet Engines*, Vol. 11, Nos. 2-3, 1994, pp. 229-242 (Also *AIAA Paper 91-1898*, June 1991).

Lawless, P. and Fleeter, S., "Prediction of Active Control of Subsonic Centrifugal Compressor Rotating Stall," *AIAA Paper 93-0153* , January 1993.

Lawless, P. and Fleeter, S., "Rotating Stall Acoustic Signature in a Low Speed Centrifugal Compressor, Part 1: Vaneless Diffuser," *ASME Paper 93-297*, May 1993.

Lawless, P. and Fleeter, S., "Rotating Stall Acoustic Signature in a Low Speed Centrifugal Compressor, Part 2: Vaned Diffuser," *ASME Paper 93- 254*, May 1993.

Lawless, P. and Fleeter, S., "A Model for the Selective Amplification of Spatially Coherent Waves in a Compressor on the Verge of Rotating Stall" *AIAA Paper 93-2236*, June 1993.

Lawless, P.B., and Fleeter, S., "Effect of Controlled Inlet Distortions on Rotating Stall Inception in a Low Speed Centrifugal Compressor", *AIAA Paper 94-2799*, June 1994.

Lawless, P.B., and Fleeter, S., "Rotating Stall Initiation And Suppression In A Centrifugal Fan," *1994 International Compressor Engineering Conference at Purdue*, July 1994.

Lawless, P., Kim, K. and Fleeter, S., "Spatial Domain Characterization of Abrupt Rotating Stall Initiation in an Axial Flow Compressor," *AIAA Journal for Propulsion and Power*, Vol. 10, No. 5, September-October 1994, pp. 709-715. (Also*AIAA Paper 93-0153* , June 1993).